ARMY RESEARCH LABORATORY

# An Evaluation of Former Soviet Union Welding Processes on Commercially Pure Titanium

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## Abstract

The U.S. Army Research Laboratory (ARL) and the U.S. Naval Surface Warfare Center (NSWC) jointly performed a preliminary investigation of advanced titanium gas tungsten arc welding (GTAW) technologies developed in the former Soviet Union (FSU). Commercially pure titanium (CP Ti) plates were supplied to the E.O. Paton Electric Welding Institute, Kiev, Ukraine, and were welded by GTAW with flux-cored filler wire, twin-arc GTAW, and narrow gap magnetically impelled GTAW. The three CP Ti weldment specimens were then evaluated at ARL and NSWC through nondestructive inspection, chemical analysis, mechanical property determination, and metallographic examination. The objective of this study was to evaluate the quality of the welds and to assess the applicability of the FSU welding techniques to U.S. Army ground vehicle and weapon system fabrication. Information is provided about visual and radiographic features, chemical composition, tensile, ductility, and bend properties, hardness profiles, and micro-structural characteristics of the base metal and weld deposits.

ACKNOWLEDGMENTS

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# Contents

## Tables

AN EVALUATION OF FORMER SOVIET UNION WELDING PROCESSES ON COMMERCIALLY PURE TITANIUM

# 1. Introduction

Titanium is being used in military ground vehicles and weapon systems because of its unique combination of mechanical properties and ballistic performance [1,2,3,4,5]. The high strength-to-weight ratio of titanium offers appreciable weight reduction (30% to 40%) when titanium replaces conventional steel armor. Additionally, the high mass efficiency of titanium armor (approximately 1.6 times that of rolled homogeneous armor [RHA]) provides excellent performance against a broad spectrum of ballistic threats as well as good multi-hit tolerance. Ti-6Al-4V is the most common titanium alloy and the alloy of choice for current and proposed structural and armor applications such as the M1A2 Abrams tank, the M2 Bradley fighting vehicle, the 155-mm ultra-lightweight field howitzer, and the future combat system.

Titanium structures and armor packages are generally fabricated by thermal joining methods common to the metals fabrication industry, with gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), and plasma arc welding (PAW) being the most widely used techniques. Of these, the GTAW process is much preferred because it is driven by precise control of the welding parameters and excellent control of root pass weld penetration. Also, GTAW produces high quality welds, is free of the spatter that may occur with GMAW, and can be used with or without filler material, depending on the specific application. Unlike welding RHA, the welding of titanium, because of its reactivity with the surrounding atmosphere at elevated temperatures, requires special considerations and tooling to prevent weld contamination.

The U.S. Army Research Laboratory (ARL) and the U.S. Naval Surface Warfare Center (NSWC) jointly performed a preliminary investigation of advanced titanium gas tungsten arc welding technologies developed in the former Soviet Union (FSU). Three techniques were studied: GTAW with flux-cored filler wire, twin-arc GTAW, and narrow gap magnetically impelled GTAW. Commercially pure titanium (CP Ti) plates provided by the U.S. Army Tank-automotive and Armaments Command (TACOM) Armament Research, Development, and Engineering Center (ARDEC), Picatinny Arsenal, New Jersey, were supplied to the E.O. Paton Electric Welding Institute, Kiev, Ukraine, where each of the three aforementioned FSU welding techniques was used to fabricate one weldment specimen. Although titanium alloys are of most interest to the U.S. Army, CP Ti was selected for this project for several reasons, including cost and the desire to evaluate the baseline titanium welding capabilities of the Paton Institute. Additionally, CP Ti is used for seawater piping systems on U.S. Navy surface

ships. A brief description of the FSU welding technologies [6,7] and procedures employed for producing the titanium weldments are described in this report. The weldment specimens were identified as Plates A, B, and C, and their respective dimensions were 152 mm L by 305 mm W by 13 mm T (6 in. L by 12 in. W by 0.5 in. T), 254 mm L by 406 mm W by 25 mm T (10 in. L by 16 in. W by 1.0 in. T), and 206 mm L by 400 mm W by 25 mm T (8.125 in. L by 15.75 in. W by 1.0 in. T). The L dimension was parallel to the weld, the W dimension was transverse to the weld, and T was the plate thickness. The objective of this study was to (a) evaluate the quality of the welds through nondestructive inspection, chemical analysis, mechanical testing, and metallographic examination, and (b) assess the applicability of the FSU welding techniques to U.S. Army ground vehicle and weapon system fabrication.

# 2. FSU Welding Technologies

## 2.1 Gas Tungsten Arc Welding With Flux-Cored Filler Wire

Titanium flux-cored wire is designed for use as a filler material in all types of GTAW in commercially pure titanium and alpha ($\alpha$) and alpha-beta ($\alpha$-$\beta$) titanium alloys 4 to 16 mm (0.16 to 0.63 in.) thick. The wire yields welds in one pass without edge preparation in the flat position, eliminates pore formation, greatly reduces welding time, argon, and energy consumption, and excludes the application of solid titanium filler wire. Welding can be performed with any equipment designed for GTAW of titanium, thus providing welded joint service characteristics at the level of the base metal. Consumption of flux-cored wire is 1.1 to 1.2 m (43.3 to 47.2 in.) per 1 m (39.4 in.) of weld. While the present level of titanium technology in the United States has not developed a flux-cored wire, extensive research in the FSU has reportedly resulted in the development of both paste fluxes and flux-cored wires [8].

## 2.2 Twin-Arc Gas Tungsten Arc Welding

The twin-arc GTAW process is a highly reproducible method for welding thick metal sections at high deposition and travel rates but with minimum melt through of the base metal. Twin-arc welding allows the second filler wire to be added at a much lower amperage level, which increases productivity while keeping the heat input low. This welding method is also useful in cases when the composition of the filler metal is different from that of the base metal.

## 2.3 Narrow Gap Magnetically Impelled Gas Tungsten Arc Welding

Developed for welding medium and heavy sections of CP Ti and $\alpha$ and $\alpha$-$\beta$ titanium alloys as thick as 110 mm (4.33 in.), narrow gap magnetically impelled GTAW reduces the process time because melting of the base metal is minimal,

and it minimizes the required amount of welding consumables and total heat input. The process is based on oscillation of the direct current negative arc used as the welding heating source from root edge to edge. Varying the frequency of the alternating magnetic field makes it possible to control the distribution of the thermal energy of the arc between the root opening edges, the filler metal, and the molten metal of the weld pool.

# 3. Welding Procedures

## 3.1 Plate A: GTAW With PPT-2 Flux-Cored Filler Wire

Plate A welding was performed in a single pass without groove preparation and on a backing strip that was then removed by milling. Normally, welding is performed with a copper backing and with a backing shielding gas, but no proper backing existed for this base plate of non-standard thickness (13 mm). According to the available information about the FSU welding procedures [9], this should have no effect on the weldment properties or on the welding operation in general. Also noted in the welding procedures information was that the limited amount of Plate A material did not allow for the optimization of welding parameters, which resulted in undercuts formed in the weld zone. The welding parameters were

Current: 450 amperes (A)
Arc voltage: 18 volts (V)
Travel speed: 7.6 m/h (5 in./min)
Number of passes: one
The calculated heat input was 97.2 kJ/in.

## 3.2 Plate B: Twin-Arc GTAW

Plate B welding was performed with U-groove preparation and with a root opening of 10 mm (0.39 in.). The root joint was welded with one electrode without filler wire in the following conditions:

Current: 440 A
Arc voltage: 12 V
Travel speed: 15 m/h (9.8 in./min)
Number of passes: one

The calculated root face heat input was 32.3 kJ/in. The remaining portion of the U-groove was then filled by twin-arc welding via VT1-00sv (ERTi-3) grade filler wire with a diameter of 4 mm (0.16 in.). The welding parameters were

Current (each electrode): 200 A
Arc voltage: 12 V
Travel speed (each pass): 7 m/h (4.6 in./min)

Number of passes: four
Filler wire feed speed: 32 m/h (21 in./min)

The calculated heat input per arc was 31.3 kJ/in.

### 3.3 Plate C: Narrow Gap Magnetically Impelled GTAW

Plate C welding was performed with VT1-00sv (ERTi-3) grade filler wire with a diameter of 4 mm (0.16 in.) and on a backing strip that was subsequently removed by milling. The gap width was 8 mm (0.32 in.), and the welding parameters were

Current: 420 A
Arc voltage: 12 V
Travel speed (each pass): 8 m/h (5.2 in./min)
Number of passes: four

The calculated heat input was 58.2 kJ/in. The FSU welding procedures information noted that the sample weld length (206 mm) was shorter than the full plate width (400 mm) since some material was sacrificed to obtain proper welding parameters.

## 4. Materials

The chemical composition and tensile properties of the base plate material reported by the supplier (Performance Alloys and Materials, Secaucus, New Jersey) are listed in Tables 1 and 2, along with the chemical composition and mechanical property requirements for Ti-CP, Grades 1 through 4 from the American Society for Testing Materials (ASTM) B265 **[10]**. The exact composition of the flux-cored wire used in fabricating the Plate A weldment was unknown, but the composition of PPT-2 weld wire from Reference 8 is given as 40% to 50% $CaF_2$, 18% to 20% $LaF_3$ or $CeF_3$, 5% to 10% $BaF_2$, and $SrF_2$ (remainder). No information was available about the composition of the wire sheath, which may be produced from commercially pure titanium or one of its alloys **[11]**. Plates B and C were welded with VT1-00sv grade filler wire (American Welding Society [AWS] A5.16 ERTi-3 wire) **[12]**. The Plate A base metal meets the ASTM B265 chemical composition and mechanical property requirements for Ti-CP, Grade 2; Plates B and C meet Grade 4 requirements; and both appear to be a high strength form of these respective grades.

Table 1. Base Metal Chemical Composition

| | N (percent) | C (percent) | H (percent) | Fe (percent) | O (percent) |
|---|---|---|---|---|---|
| Plate A Base Metal | 0.013 | 0.016 | 0.0016 | 0.23 | 0.132 |
| Plate B Base Metal | 0.013 | 0.006 | 0.0016 | 0.37 | 0.295 |
| Plate C Base Metal | 0.011 | 0.009 | 0.0014 | 0.38 | 0.302 |
| Ti-CP Specification | | | | | |
| ASTM B265, Grade 1 | 0.03 max | 0.08 max | 0.015 max | 0.20 max | 0.18 max |
| ASTM B265, Grade 2 | 0.03 max | 0.08 max | 0.015 max | 0.30 max | 0.25 max |
| ASTM B265, Grade 3 | 0.03 max | 0.08 max | 0.015 max | 0.30 max | 0.35 max |
| ASTM B265, Grade 4 | 0.03 max | 0.08 max | 0.015 max | 0.50 max | 0.40 max |

Note: The reported percent oxygen for Plates B and C is the average of two measurements.

Table 2. Base Metal Tensile Property Data

| | Tensile Strength, MPa (ksi) | 0.2% Yield Strength, MPa (ksi) | Elongation, (percent) |
|---|---|---|---|
| Plate A | 517 (75) | 400 (58) | Not reported |
| Plates B and C | 703 (102) | 545 (79) | Not reported |
| Ti-CP Specification | | | |
| ASTM B265, Grade 1 | 240 (35) min | 170 (25) min, 310 (45) max | 24 min |
| ASTM B265, Grade 2 | 345 (50) min | 275 (40) min, 450 (65) max | 20 min |
| ASTM B265, Grade 3 | 450 (65) min | 380 (55) min, 550 (80) max | 18 min |
| ASTM B265, Grade 4 | 550 (80) min | 485 (70) min, 655 (95) max | 15 min |

# 5. Results and Discussion

## 5.1 Nondestructive Inspection

Visual examination of the weld surfaces did not reveal any indications of brushing or grinding, and the surface appeared in an as-deposited condition. The color of the weld surfaces was a lustrous silver. The absence of surface color indicated that the slag covering on Plate A (GTAW with flux-cored filler wire)

effectively shielded the solidified weld from oxygen contamination and that a trailing shield was used during welding of Plates B and C (twin-arc GTAW and narrow gap magnetically impelled GTAW, respectively), although this was not indicated in the FSU welding procedure information. A slight degree of under-fill was observed along the fusion line on each side of the weld metal on Plate A; no under-fill was observed on Plates B and C.

Radiographic inspection of the weldments revealed the following:

Plate A: No indications of cracking, porosity, or incomplete fusion in the weld or along the side walls of the joint.

Plate B: Numerous, uniformly distributed pores as well as aligned porosity were observed in the weld metal. The diameter of the individual pores ranged in size from 1.3 mm (0.051 in.) to 1.6 mm (0.063 in.), and the length of the largest aligned porosity was 13.3 mm (0.52 in.). A single tungsten inclusion adjacent to a pore site was also observed, with the longest dimension of this double discontinuity being 2.0 mm (0.078 in.). There were no indications of cracking or incomplete fusion in the weld metal or along the side walls of the joint.

Plate C: No indications of cracking, inclusions, or incomplete fusion in the weld metal or along the side walls of the joint. However, several pores were observed in the weld metal, with the largest being 1.3 mm (0.078 in.) in diameter.

## 5.2 Chemical Analysis

The chemical composition of the three weld metals is presented in Table 3, along with the specification requirements for ASTM B265 Ti-CP, Grades 1 through 4 and for AWS A5.16 ERTi-3 weld wire. The weld metals meet the chemical composition requirements for all elements except for nitrogen in Plate A (GTAW with flux-cored filler wire), which significantly exceeds those allowed by the specification. While the extent of the interstitial and iron pickup is unknown because information about the wire chemistry is lacking, nitrogen contamination of the weld with the $CaF_2$-based flux is consistent with the literature **[13]**. It is noted that the 0.03% nitrogen level in the Plate C weld metal, although meeting the ASTM B265 specification, exceeds the nitrogen level of AWS A5.16.

Table 3. Chemical Composition of the Weld Metals

| | N (percent) | C (percent) | H (percent) | Fe (percent) | O (percent) |
|---|---|---|---|---|---|
| Plate A: PPT-2 | 0.071 | 0.016 | 0.0017 | 0.20 | 0.159 |
| Plate B: ERTi-3 | 0.008 | 0.009 | 0.0021 | 0.09 | 0.061 |
| Plate C: ERTi-3 | 0.030 | 0.009 | 0.0026 | 0.14 | 0.142 |
| Ti-CP Specification | | | | | |
| ASTM B265, Grade 1 | 0.03 max | 0.08 max | 0.015 max | 0.20 max | 0.18 max |
| ASTM B265, Grade 2 | 0.03 max | 0.08 max | 0.015 max | 0.30 max | 0.25 max |
| ASTM B265, Grade 3 | 0.03 max | 0.08 max | 0.015 max | 0.30 max | 0.35 max |
| ASTM B265, Grade 4 | 0.03 max | 0.08 max | 0.015 max | 0.50 max | 0.40 max |
| ERTi-3 Specification | | | | | |
| AWS A5.16 | 0.02 max | 0.03 max | 0.008 max | 0.20 max | 0.10-0.15 max |

## 5.3 Hardness Measurements

Diamond pyramid (Vickers) hardness measurements at a load of 500 grams were performed across the base metal, the heat-affected zone (HAZ) and at the weld metal surface and through the weld thickness. Table 4 lists the average value of these measurements converted to Rockwell B hardness.

The Plate A hardness values were essentially the same at all measurement locations, including at the surface and through the thickness of the weld. Nitrogen contamination of the weld, as evidenced by the excessive level determined by chemical analysis (see Table 3), could be expected to take place by nitrogen diffusing through the slag and into the solidified weld, thus producing a hardened surface layer. However, the absence of a distinct hardened layer indicated that interstitial contamination of the weld likely occurred as a result of the absorption of nitrogen into the liquid weld puddle. The Plate B weld metal hardness data were typical for a welded joint in which the interstitial pickup of nitrogen, carbon, hydrogen, and carbon was minimal. The higher hardness of the Plate C weld metal, as compared with that of Plate B, is consistent with the higher interstitial content, which may have been caused by a number of reasons but was probably attributable to contaminants in the shielding gas or inadequate gas coverage.

Table 4. Rockwell B Hardness Values From the Weldment Specimens

| | Base Metal | Weld Metal Surface | Weld Metal Through Thickness | Heat-Affected Zone |
|---|---|---|---|---|
| Plate A | 88.7 | 92.0 | 91.5 | 89.7 |
| Plate B | 97.4 | 76.9 | 77.1 | 98.1 |
| Plate C | 97.1 | 90.9 | 86.4 | 99.3 |

### 5.4 Tensile Property Determination

The tensile property data from the base metal and all-weld-metal specimens are provided in Table 5, along with the ASTM B265 specification requirements for Ti-CP, Grades 1 through 4. Also listed are the type of specimen tested and the orientation of the specimen test, with longitudinal being parallel to the weld and transverse being orthogonal to the weld. Plate A weld metal was tested with a 6.4-mm (0.25-in.) diameter round, sub-size specimen with a 25.4-mm (1.0-in.) gauge length. The Plate B base and all-weld metal round, sub-size tensile specimens measured 9.1 mm (0.36 in.) in diameter and had a gauge length of 35.6 mm (1.40 in.) and were designated Type TR-2A **[14]**. Because of the limited amount of Plate C material (the length of the weld deposit was only 206 mm [8.125 in.]), all-weld metal tensile testing was not performed. Plates B and C plate-type transverse specimens were 229 mm (9.0 in.) long, 19 mm (0.75 in.) wide in the gauge section, and 25 mm (1.0 in.) thick. These full plate thickness specimens were composed of the deposited weld metal, the HAZ, and the unaffected base metal. Plate A plate-type tensile testing was not performed, again because of the limited size of weldment material.

The Plate A weld metal yield strength exceeded the maximum allowable ASTM B265 requirement for Ti-CP, Grade 2, and the elongation failed to meet the minimum requirement of 20%. The elevated strength properties of the flux-cored weldment were attributed primarily to the nitrogen content of the weld metal, since this is a potent strengthener in titanium. The base metal tensile data from Plate B met the Grade 4 requirements and were comparable to the values reported by the supplier (see Table 2). The Plate B weld metal tensile and yield strengths and elongation results from the three plate-type transverse specimens tested also met the Grade 4 requirement. The face weld metal tensile property data from an all-weld metal longitudinal specimen met the strength and elongation requirements of Ti-CP, Grade 2, consistent with the low interstitial content of the ERTi-3 weld wire and as analyzed in the chemical composition of the Plate B weld metal (see Table 3). The Plate B root weld metal exceeded the maximum allowable yield strength of Grade 2, and the elongation failed to meet the 20% minimum requirement. Examination of the weld face tensile specimen

showed two necking sites, both of which were outside the extensometer mounting range.

Table 5. Tensile Property Data From the Base and Weld Metals

| Plate, Material, Specimen Number | Specimen Type, Specimen Test | Tensile Strength, MPa (ksi) | 0.2% Yield Strength, MPa (ksi) | Elongation, (percent) |
|---|---|---|---|---|
| A, Weld Metal, No. 1 | Round, Long. | 634 (92) | 545 (79) | 16 |
| B, Base Metal, No. 1 | Round, Trans. | 696 (101) | 558 (81) | 22 |
| B, Base Metal, No. 2 | Round, Trans. | 648 (94) | 517 (75) | 23 |
| B, Face Weld Metal, No. 1 | Round, Long. | 421 (61) | 352 (51) | 22 |
| B, Root Weld Metal, No. 1 | Round, Long. | 627 (91) | 565 (82) | 10 |
| B, Weld Metal, No. 1 | Plate, Trans. | 614 (89) | 503 (73) | 15 |
| B, Weld Metal, No. 2 | Plate, Trans. | 607 (88) | 496 (72) | 14 |
| B, Weld Metal, No. 3 | Plate, Trans. | 607 (88) | 490 (71) | 15 |
| C, Weld Metal, No. 1 | Plate, Trans. | 586 (85) | 483 (70) | 12 |
| C, Weld Metal, No. 2 | Plate, Trans. | 593 (86) | 496 (72) | 7 |
| C, Weld Metal, No. 3 | Plate, Trans. | 593 (86) | 490 (71) | 8 |

| Ti-CP Specification | Tensile Strength, MPa (ksi) | 0.2% Yield Strength, MPa (ksi) | Elongation, (percent) |
|---|---|---|---|
| ASTM B265, Grade 1 | 240 (35) min | 170 (25) min, 310 (45) max | 24 min |
| ASTM B265, Grade 2 | 345 (50) min | 275 (40) min, 450 (65) max | 20 min |
| ASTM B265, Grade 3 | 450 (65) min | 380 (55) min, 550 (80) max | 18 min |
| ASTM B265, Grade 4 | 550 (80) min | 485 (70) min, 655 (95) max | 15 min |

Long. = longitudinal Trans. = transverse

Calculation of percent elongation, based on the measured fracture specimen, resulted in an estimated elongation exceeding 50%. The elevated strength and lack of root ductility was probably caused by the root joint being welded without filler wire and with different parameters than were used for the remainder of the U-groove. The Plate B transverse specimens met the ASTM B265 requirements for Ti-CP, Grade 4. However, the Plate C transverse specimens failed, based on low measured elongation. A possible explanation of this could lie within the fact that the same size extensometer was used to measure both specimens. It must be understood that the actual width of the weld metal in Plate C was smaller than the width of Plate B. This difference has been measured at approximately a 3:2 ratio. If the elongation occurred primarily within the weld zone and one measured the elongation over a greater distance, then one would obtain artificially low elongation data since the elongation was not uniform throughout the sample. This fact is sometimes observed in non-homogeneous specimens such as transverse weld specimens. The actual elongation data yielded a 5:3 ratio for Plate B to Plate C, quite similar to the comparison of their respective weld metal widths. If a smaller extensometer were used to measure the elongation of Plate C,

it is speculated that the data would be consistent with Ti-CP, Grade 4. A lack of additional material prevented the testing of this hypothesis.

## 5.5 Bend Test

The bend radius for the bend ductility tests was determined by the minimum base metal elongation in accordance with AWS B4.0 **[15]**. As noted previously, Plate A met the chemical composition and mechanical property requirements for Ti-CP, Grade 2. For commercially pure titanium material with a minimum elongation requirement of 20%, the bend radius is 2T over a 180-degree bend, where T is equal to the specimen thickness. One bend specimen removed from the Plate A weldment and tested at 2T failed to meet the bend requirement of Naval Sea Systems Command (NAVSEA) Technical Publication S9074-AQ-GIB-010/278 **[16]**; a second specimen tested at 4T passed. The 2T bend radius was also applied to bend specimens from Plates B and C, based on the elongation results from Plate B shown in Table 5. All bend specimens tested at the 2T radius failed. No additional bend tests were performed on Plates B and C. It is noted that ASTM B265 requires a 4T bend over 105° for Ti-CP, Grade 2 material.

## 5.6 Metallographic and Microstructural Examination

### 5.6.1 Plate A: GTAW With PPT-2 Flux-Cored Filler Wire

A macrosection from the flux-cored weldment is provided in Figure 1. The macrostructure showed a single weld pass that was characterized by the formation of large columnar grains that initiated at the solid-liquid interface. The relatively wide HAZ was attributed to the high heat input (97.2 kJ/in.) used in fabricating the weldment.

The aspect ratio (weld depth to width) is provided in Table 6, along with typical values for conventional gas tungsten arc welds in commercially pure titanium (CP Ti) with the same parameters and joint design as employed in fabrication of the flux-cored weldment. A comparison of the weld bead dimensions showed that the flux formulation was effective in increasing weld penetration as compared with conventional GTAW of titanium with argon shielding. The increase in weld penetration was greater than 2x.

The weld metal microstructure is shown in Figure 2 and was typical of microstructures that form in CP Ti weld metal on cooling from above the beta-transus temperature. The structure consisted predominantly of course acicular alpha ($\alpha$) along with evidence of prior beta ($\beta$) grain boundaries. Acicular $\alpha$ forms in titanium by a nucleation and growth process and can exist as fine or thick platelets, depending on the weld metal cooling rate. The course $\alpha$ platelets shown in Figure 2 were attributed to a slow cooling rate resulting from the high heat input (97.2 kJ/in.). There was some evidence of serrated $\alpha$, characterized by

irregular grain size and jagged grain boundaries that form in commercially pure titanium weld metal of high purity.


Figure 1. Macrosection From the Flux-Cored Weldment.

Table 6. Flux-Cored Weld Bead Dimensions

| Material | Weld Width, mm (in.) | Depth of Penetration, mm (in.) | Aspect Ratio |
|---|---|---|---|
| Flux-Cored Weld | 16 (0.63) | 13.5 (0.53) | 0.84 |
| Conventional Weld | 15 (0.59) | 6.0 (0.24) | 0.40 |

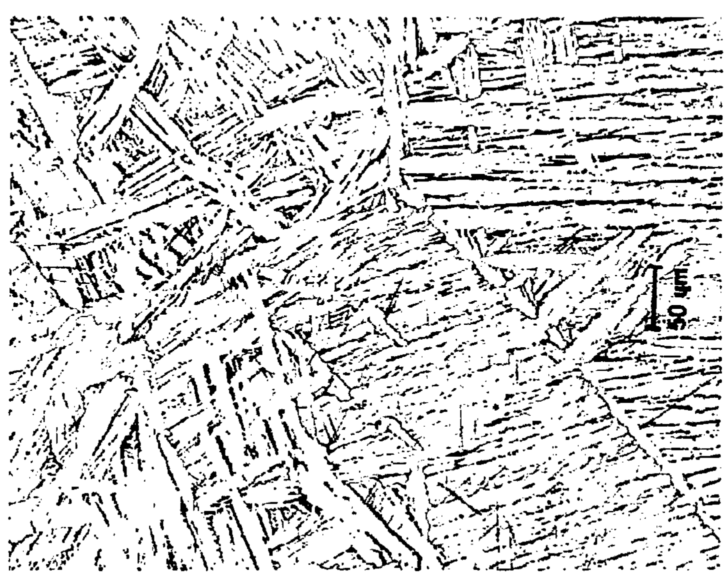


Figure 2. Microstructure of the PPT-2 Weld Metal.

### 5.6.2 Plate B: Twin-Arc GTAW

The commercially pure titanium base metal was characterized by elongated grains of $\alpha$ (from the rolling process) with distributed equiaxed $\alpha$ grains (from the cold working) that were predominantly located at the grain boundaries. The base plate microstructure is observable in Figure 3 and was representative of CP Ti plate. A photomacrograph of a cross section prepared from the twin-arc GTAW weldment is shown in Figure 4. The macrograph depicts a root face bead of approximately 5.6 mm (0.22 in.) by 1.9 mm (0.075 in.) penetrating approximately 6.4 mm (0.25 in.) into the weldment.

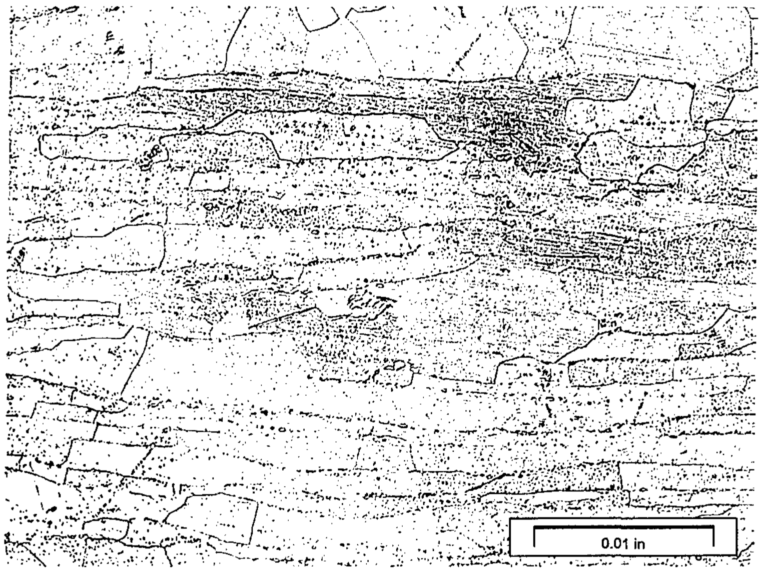


Figure 3. Microstructure of the Plate B Base Metal (Etchant: Kroll's Reagent).

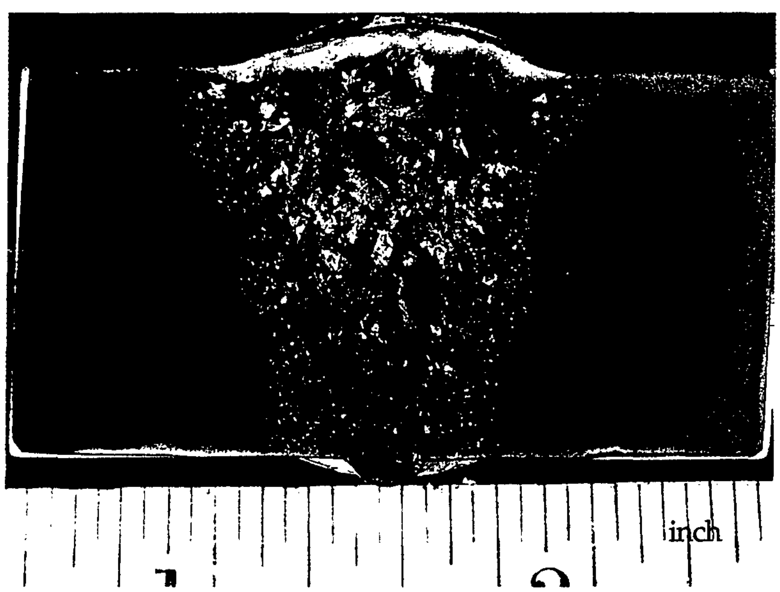


Figure 4. Photomacrograph of a Cross Section From the Twin-Arc Weldment (Etchant: Kroll's Macro Etchant).

This root face was used instead of a backing strip. Two passes with a twin-arc electrode (for a total of four passes, excluding the root pass) are observable, as well as the root face pass. The macrostructure of the weldment demonstrated semi-equiaxed grains, with the largest being at the surface near the weld bead and the smallest grains dissipating into the HAZ as would be expected for conventional GTAW. The HAZ was narrower than normal, approximately 5.0 mm (0.2 in.) wide. This was attributed to the relatively low heat input for this process (31.3 kJ/in.). The base metal-HAZ boundary is depicted in Figure 5.

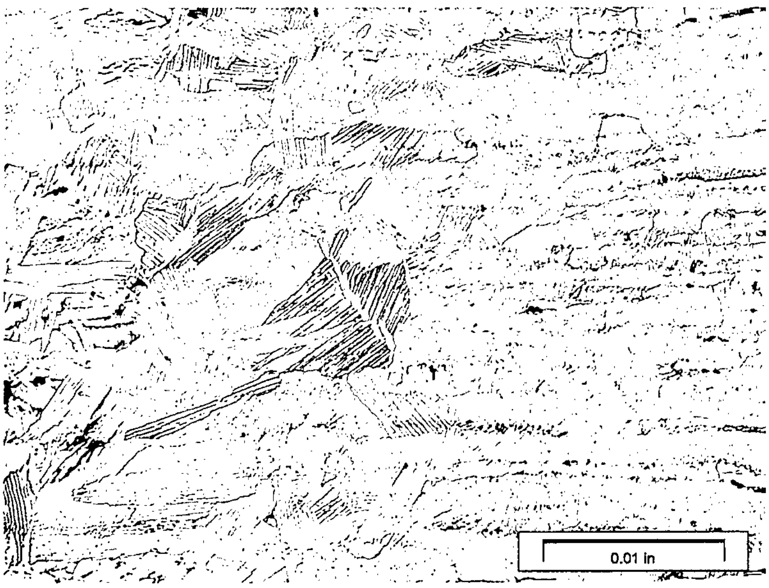


Figure 5. Microstructure of the Base Metal-HAZ Boundary (Etchant: Kroll's Reagent).

The base metal structure is to the right in the photo. The transition from grains affected by the heat input to those that were unaffected is clearly discernible. The HAZ microstructure of Plate B is depicted in Figure 6. The structure consisted almost entirely of coarse acicular $\alpha$ platelets. Evidence existed of serrated $\alpha$, characterized by the irregularly shaped grains and the $\alpha$ extending across the non-distinct grain boundaries. The structure is shown at higher magnification in Figure 7.

The weld bead microstructure consisted of fine acicular $\alpha$ and was representative of CP Ti welds (with CP filler wire) that air cool from above the beta-transus temperature. The structure is shown in Figure 8. It can be contrasted with the structure of the HAZ (see Figure 6) in that the platelets of acicular $\alpha$ are much finer from the rapid solidification within the weld pool.

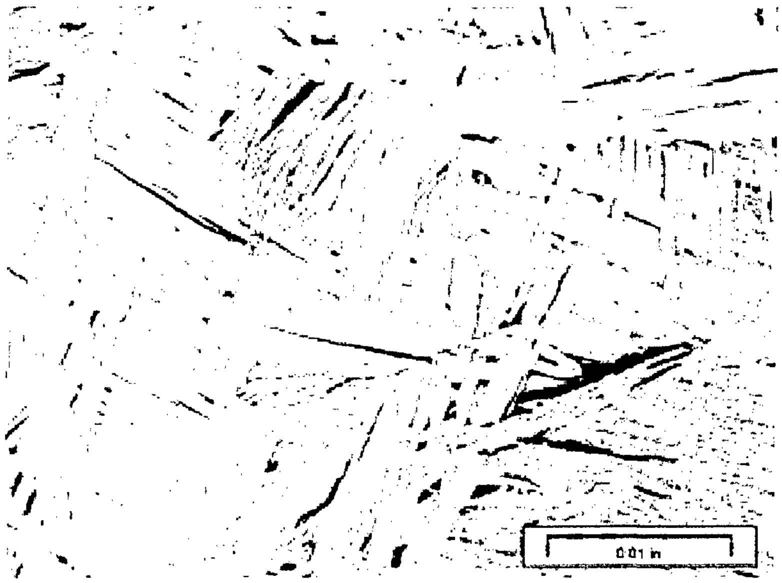


Figure 6. HAZ Microstructure Consisting of Acicular α (Etchant: Kroll's Reagent).

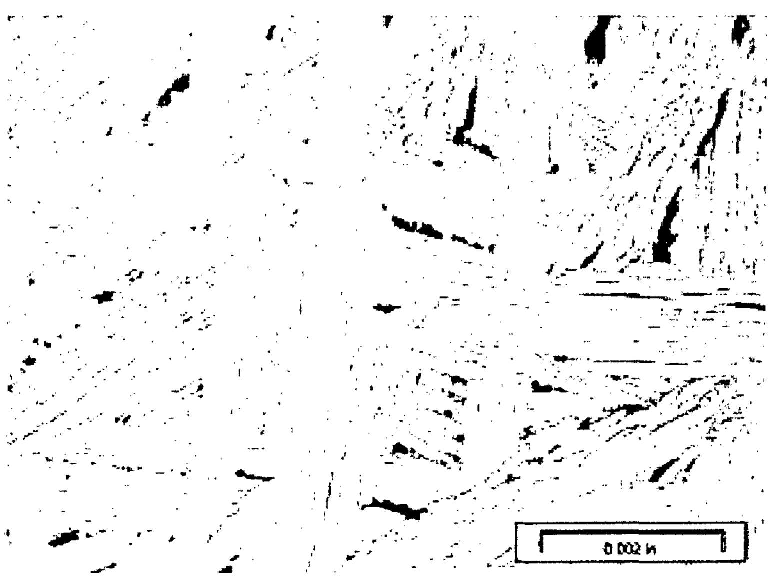


Figure 7. Higher Magnification of the HAZ Microstructure in Figure 6 (Etchant: Kroll's Reagent).

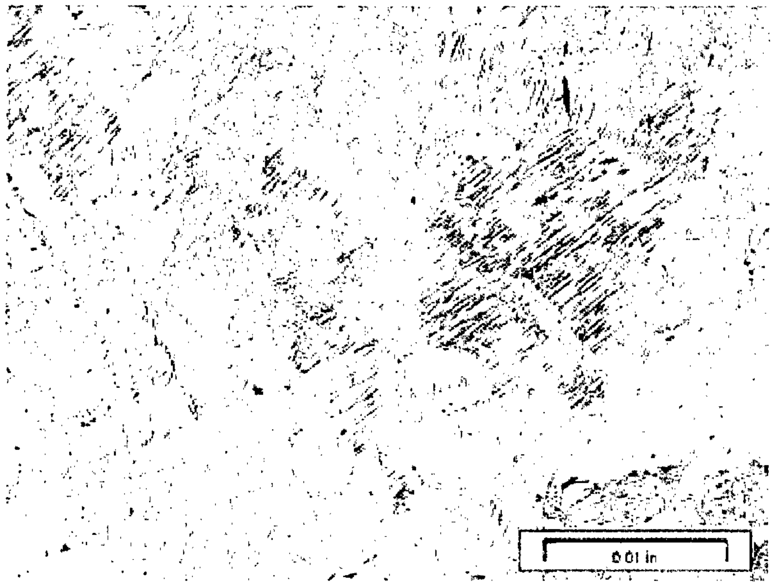

Figure 8. Weld Bead Microstructure Characterized by Fine Acicular α (Etchant: Kroll's Reagent).

The weld metal had two regions of micro-porosity, both of which were very small in area. One of the two regions is shown in Figure 9.

The region consisted of three small gas bubble holes formed during solidification after welding. The total area of porosity within the weld was estimated to be no greater than 0.015%.

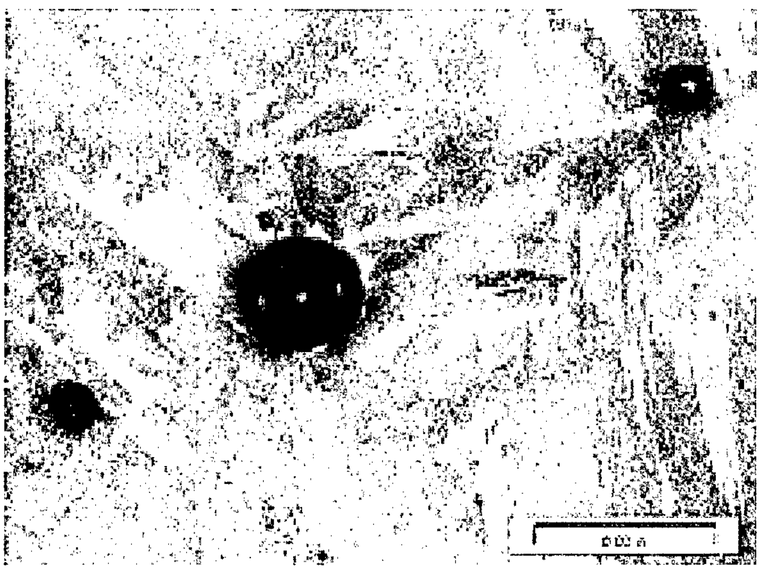

Figure 9. Microporosity Within the Twin-Arc Weldment (Etchant: Kroll's Macro Etchant).

### 5.6.3 Plate C: Narrow Gap Magnetically Impelled GTAW

A photomacrograph of a cross section prepared from the narrow gap magnetically impelled GTAW weldment is shown in Figure 10. A backing strip was used during the welding process (the HAZs at the edge of the backing plate are visible in the figure). Four passes of the electrode are clearly discernible. The macrostructure of the weldment demonstrated semi-equiaxed grains, with the largest being at the surface near the weld bead and the smallest grains dissipating into the HAZ, as would be expected for conventional GTAW. The overall weld area was narrower than normal for this plate thickness and was only approximately 10 mm (0.4 in.) wide. The weld area was unusually consistent in width through the thickness of the plate. This was directly linked to the application of the alternating magnetic field during the welding process. The application of the magnetic field made the weld more uniform through the thickness and minimized the total thickness of the weld. The HAZ was of conventional size and was consistent with the total heat input calculated at 58.2 kJ/in. Conventional GTAW of this plate thickness with this heat input would yield a total weld area approximately twice as wide. The commercially pure titanium base metal was characterized by elongated grains of $\alpha$ (from the rolling process) with distributed equiaxed $\alpha$ grains (from the cold working) that were somewhat preferentially located at the grain boundaries. The same material was also used in the fabrication of the twin-arc GTAW weldment (Plate B). The base metal microstructure is shown in Figure 3 and was representative of commercially pure titanium plate. The base metal-HAZ boundary is depicted in Figure 11, with the base metal structure on the left in the photo. The transition from grains affected by the heat input to those that were unaffected is clearly discernible.

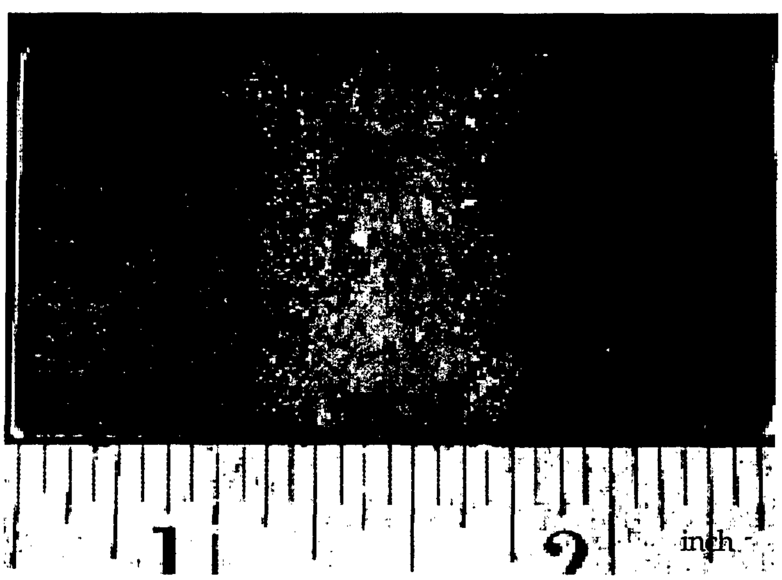


Figure 10. Photomacrograph of a Cross Section From the Narrow Gap Magnetically Impelled Weldment (Etchant: Kroll's Macro Etchant).

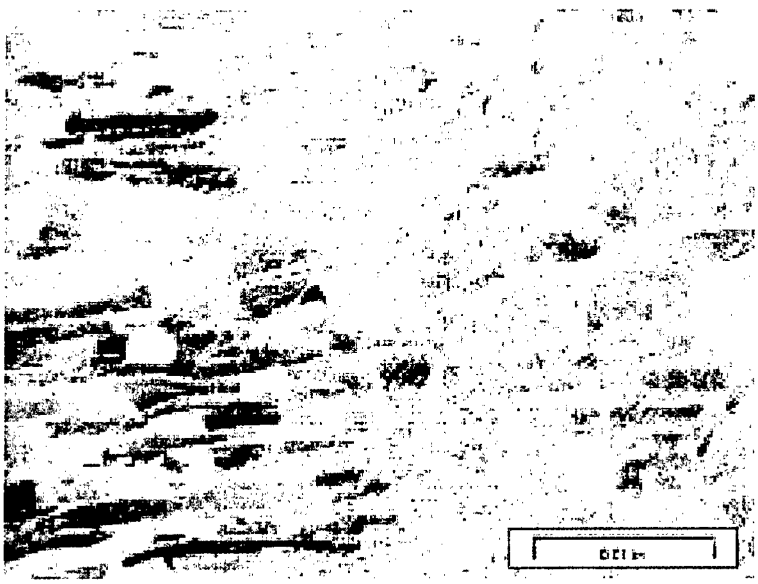

Figure 11. Microstructure of the Base Metal-HAZ Boundary (Etchant: Kroll's Reagent).

The HAZ microstructure of Plate C is depicted in Figure 12. The structure consisted almost entirely of acicular $\alpha$ platelets (light) but had some retained $\beta$ (dark). Evidence existed of serrated $\alpha$, characterized by the irregularly shaped grains and the $\alpha$ extending across the non-distinct grain boundaries. The structure is shown at higher magnification in Figure 13. It can be contrasted with the structure of the HAZ of the twin-arc GTAW weldment (see Figures 6 and 7) in that there was more heat input (58.2 kJ/in.) in the narrow gap magnetically impelled GTAW weldment, which caused higher temperatures. However, the varying magnetic field minimized base metal melting and yielded finer acicular $\alpha$ platelets (faster cooling) and more $\beta$ phase. The weld bead microstructure consisted of very fine acicular $\alpha$ and was representative of CP Ti welds (with CP filler wire) that air cool from above the beta-transus temperature. The structure is shown in Figure 14. It can be contrasted with the HAZ microstructure (see Figures 12 and 13) in that the platelets of acicular $\alpha$ are much finer from the rapid solidification within the weld pool and the varying magnetic field induced. The weld metal had two regions of microporosity, both of which were very small in area. One of the two regions is shown in Figure 15. The region consisted of a small gas bubble hole formed during solidification after welding. The total area of porosity within the weld was estimated to be no greater than 0.015%.

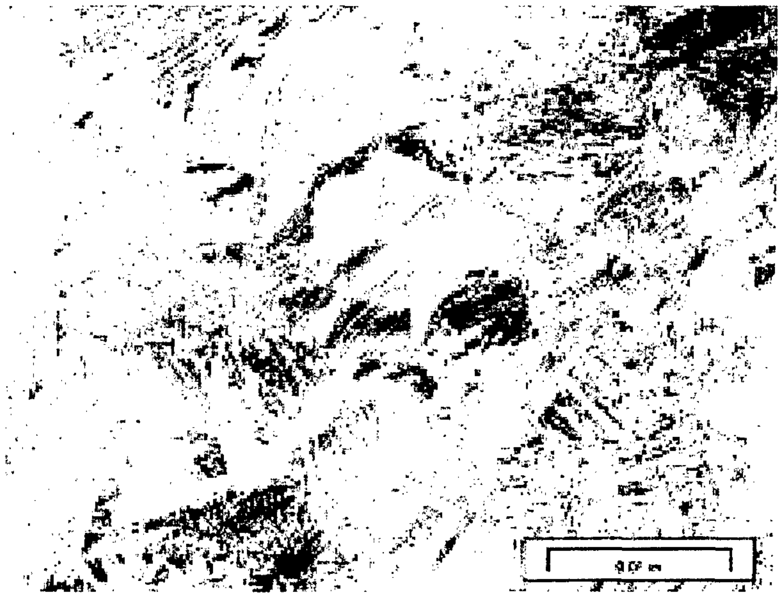

Figure 12. HAZ Microstructure Consisting of Acicular α and β Phase (Etchant: Kroll's Reagent).

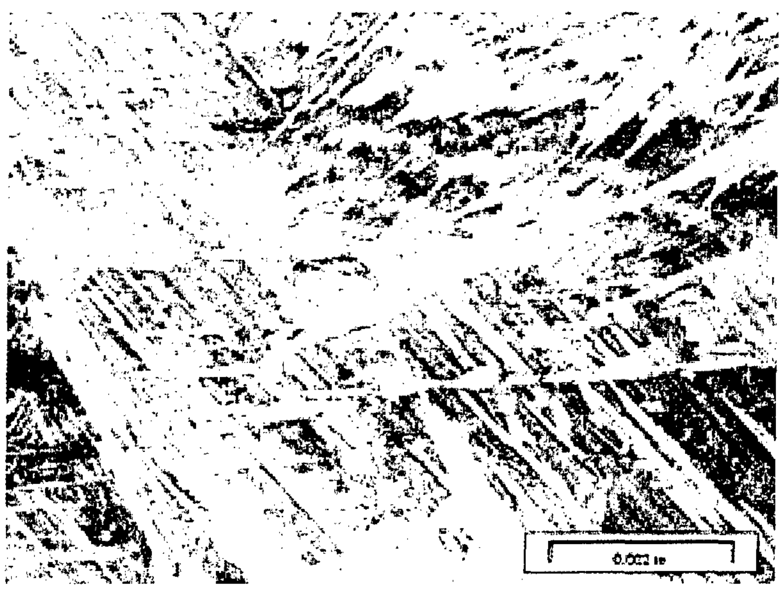

Figure 13. Higher Magnification of the HAZ Microstructure in Figure 12 (Etchant: Kroll's Reagent).

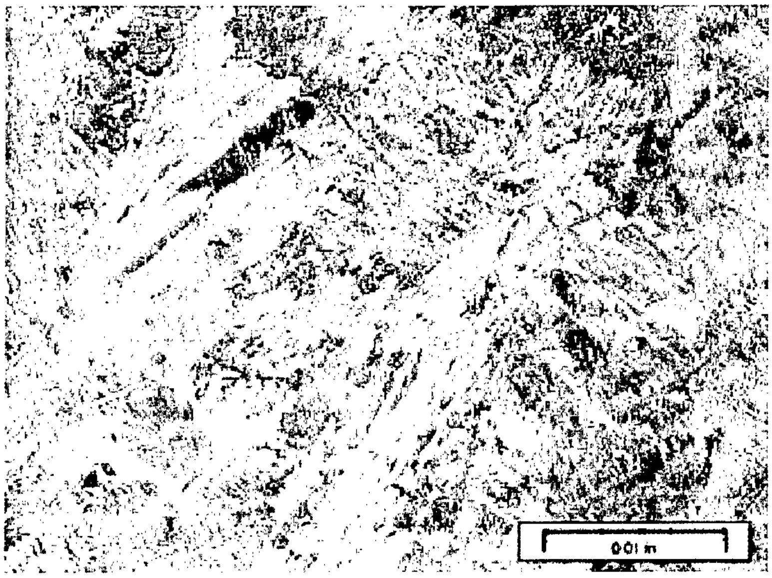

Figure 14. Weld Bead Microstructure Characterized by Fine Acicular α (Etchant: Kroll's Reagent).

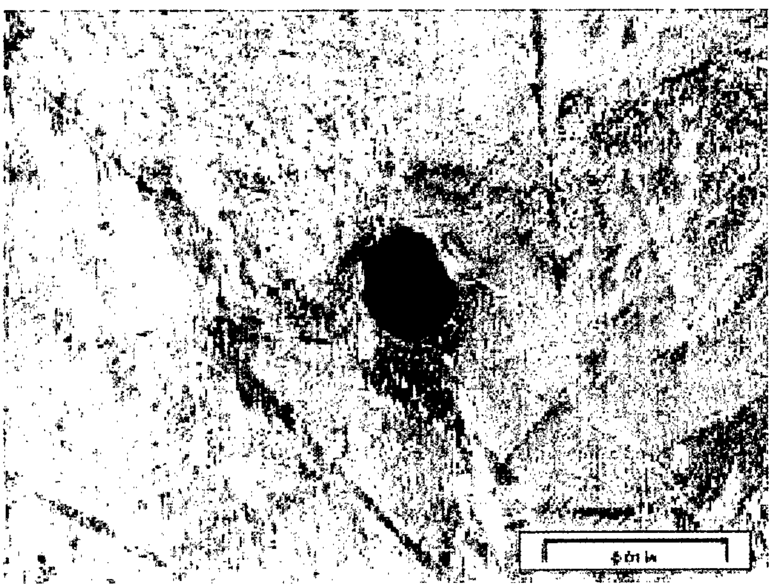

Figure 15. Microporosity Within the Narrow Gap Magnetically Impelled Weldment (Etchant: Kroll's Reagent).

# 6. Summary

## 6.1 Plate A: GTAW With PPT-2 Flux-Cored Filler Wire

The results of nondestructive inspection showed that the flux-cored wire and the welding procedures used to fabricate the weldment resulted in a sound weld with no indications of cracking or other internal defects. Chemical analysis of the weld metal ascertained acceptable carbon, hydrogen, iron, and oxygen levels in accordance with the requirements of ASTM B265 for Grade 2 commercially pure titanium plate. The nitrogen content of the weld deposit well exceeded the specification allowable. The weld metal yield strength and elongation did not meet the specification mechanical property requirements. One bend ductility test failed to meet the 2T radius bend requirement of NAVSEA Technical Publication S9074-AQ-GIB-010/278; a second specimen tested at a 4T radius bend met the requirement. The elevated tensile and yield strength properties and low elongation are attributed to nitrogen contamination of the weld metal.

## 6.2 Plate B: Twin-Arc GTAW

Radiographic inspection revealed numerous uniformly distributed pores as well as aligned porosity. The diameter of the individual pores ranged in size from 1.3 mm (0.051 in.) to 1.6 mm (0.063 in.), and the length of the largest aligned porosity was 13.3 mm (0.52 in.). There were no indications of cracking or incomplete fusion in the weld metal or along the side walls of the joint. The weld metal data satisfied the chemical composition requirement for Ti-CP, Grade 4 per ASTM B265, and the tensile and yield strengths and elongation values from the full thickness plate-type specimens met the Grade 4 mechanical property requirements. The Plate B face weld metal met the strength and elongation requirements of Ti-CP, Grade 2, but the root weld metal yield strength exceeded the Grade 2 maximum allowable, and the elongation failed to meet the 20% minimum requirement. The elevated strength and lack of root ductility were probably caused by the root joint being welded without filler wire and with different parameters than were used for the remainder of the U-groove. A single bend ductility test failed to meet the NAVSEA requirement for a 2T radius bend.

## 6.3 Plate C: Narrow Gap Magnetically Impelled GTAW

No indications of cracking, inclusions, or incomplete fusion were detected in the weld metal or along the side walls of the joint. However, several pores were observed in the weld metal, with the largest being 1.3 mm (0.078 in.) in diameter. Analysis of the chemical composition of the weld metal resulted in acceptable levels of nitrogen, carbon, hydrogen, iron, and oxygen, in accordance with the requirements of ASTM B265 for Ti-CP, Grade 4. The Plate C full thickness transverse specimens failed to meet the specified minimum requirements for

elongation. A possible explanation of this could lie within the fact that the same size extensometer was used to measure all the plate-type specimens. Since the width of the Plate C weld metal, represented by Figure 10, was approximately two-thirds that of Plate B (see Figure 4), using a smaller extensometer would have yielded a more representative elongation, most likely complying with the Grade 4 requirements. A single bend ductility test failed to meet the NAVSEA requirement for a 2T radius bend.

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13. ABSTRACT *(Maximum 200 words)*

The U.S. Army Research Laboratory (ARL) and the U.S. Naval Surface Warfare Center (NSWC) jointly performed a preliminary investigation of advanced titanium gas tungsten arc welding (GTAW) technologies developed in the former Soviet Union (FSU). Commercially pure titanium (CP Ti) plates were supplied to the E.O. Paton Electric Welding Institute, Kiev, Ukraine, and were welded by GTAW with flux-cored filler wire, twin-arc GTAW, and narrow gap magnetically impelled GTAW. The three CP Ti weldment specimens were then evaluated at ARL and NSWC through nondestructive inspection, chemical analysis, mechanical property determination, and metallographic examination. The objective of this study was to evaluate the quality of the welds and to assess the applicability of the FSU welding techniques to U.S. Army ground vehicle and weapon system fabrication. Information is provided about visual and radiographic features, chemical composition, tensile, ductility, and bend properties, hardness profiles, and micro-structural characteristics of the base metal and weld deposits.

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